Relevance of the CDMSII events for mirror dark matter

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Mirror dark matter offers a framework to explain the existing dark matter direct detection experiments, including the impressive DAMA annual modulation signal. Here we examine the implications of mirror dark matter for experiments like CDMSII/Ge and XENON10 which feature higher recoil energy threshold than the DAMA NaI experiments. We show that the two events seen in the CDMSII/Ge experiment are consistent with the interactions of the anticipated heavy $\sim Fe'$ component. This interpretation of the CDMSII/Ge events is a natural one given that a) mirror dark matter predicts an event rate which is sharply falling with respect to recoil energy and b) that the two observed events are in the low energy region near threshold. Importantly this interpretation of the CDMSII events can be checked by on-going and future experiments, and we hereby predict that the bulk of the events will be in the $E_R \overset{<}{\sim} 18$ keV region.

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Recently the CDMS collaboration[1] have announced two dark matter candidate events from their final analysis containing 612 kg-days of raw exposure on a Germanium target. These two events have recoil energies of 12.3 keV and 15.5 keV, which belong to the energy region just above the experimental threshold energy of 10 keV. The background estimate for the *entire* 10-100 keV region is around 0.8 events. However, the fact that *both* events are in the low energy part of the spectrum provides an interesting hint that these events are dark matter induced. In fact, theoretical studies within the mirror dark matter framework predicted[2] that any positive signal obtained by CDMS and similar experiments should be in the low recoil energy region near threshold. Moreover the background for this low energy (10-20 keV) 'signal' region is likely 0.2 events or less for the 612 kg-day exposure, and thus the observation of two events in the 10-20 keV recoil energy range can be viewed as interesting evidence for mirror dark matter.

Recall, mirror dark matter posits that the inferred dark matter in the Universe arises from a hidden sector which is an exact copy of the standard model sector[3] (for a review and more complete list of references see ref.[4])[2]. That is, a spectrum of dark matter particles of known masses are predicted: $e', H', He', O', Fe', ...$ (with $m_{e'} = m_e, m_{H'} = m_H$, etc). The galactic halo is then presumed to be a spherically distributed self interacting mirror particle plasma comprising these particles. Such a plasma would radiatively cool on a time scale of a few hundred million years unless a significant heat source exists. It turns out that ordinary supernova can supply the required energy if ordinary and mirror particles interact with each other via (renormalizable) photon-mirror photon kinetic mixing[3, 6]:

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \tag{1}$$

where $F_{\mu\nu}$ ($F'_{\mu\nu}$) is the ordinary (mirror) $U(1)$ gauge boson field strength tensor. Matching the rate of energy lost in the galactic halo due to radiative cooling with the energy supplied by ordinary supernova's (the fundamental process being kinetic mixing induced plasmon decay into $e'^+e'^-$ in the supernova core) gives an estimate[7] of $\epsilon \sim 10^{-9}$. Importantly, a mirror sector with kinetic mixing of this magnitude is consistent with all known laboratory, astrophysical and cosmological constraints[8], and crucially such values of ϵ make the theory experimentally testable via dark matter direct detection experiments.

The most sensitive dark matter direct detection experiment to mirror dark matter happens to be the impressive DAMA/NaI[9] and DAMA/Libra experiments[10]. The low recoil energy threshold (2 keV) of these experiments makes them sensitive to the elastic scattering of a putative $\sim O'$ component off the target nuclei. It turns out that the annual modulation signal obtained by the DAMA experiments can be fully explained and yields a measurement of ϵ[2]:

$$\epsilon \sqrt{\frac{\xi_{O'}}{0.1}} = (1.0 \pm 0.3) \times 10^{-9} \tag{2}$$

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[2]Note that successful big bang nucleosynthesis (BBN) and successful large scale structure (LSS) requires effectively asymmetric initial conditions in the early Universe, $T' \ll T$ and $n_{b'}/n_b \approx 5$. See ref.[5] for further discussions.

where $\xi_{A'} \equiv n_{A'} m_{A'} / (0.3 \; GeV/cm^3)$ is the halo mass fraction of the species A'. Other, but more tentative evidence for mirror dark matter has emerged recently from an analysis of the CDMS electron scattering data[11]. It was shown[12] that the CDMS electron scattering data can be interpreted in terms of e' scattering on electrons, and suggests

$$\epsilon \approx 0.7 \times 10^{-9} \; . \tag{3}$$

However CDMSII[1] and XENON10[13] are the most sensitive experiments to a heavier $\sim Fe'$ component and a positive signal for CDMS and similar experiments has been anticipated[14]. We will show that interpreting the two events identified in the CDM-SII/Ge analysis as an Fe' signal is consistent with all other experiments, and yields the estimate:

$$\epsilon \sqrt{\frac{\xi_{Fe'}}{10^{-3}}} \approx 10^{-9} \; . \tag{4}$$

The interaction rate for an experiment like CDMS depends on the cross-section, $d\sigma/dE_R$, and halo velocity distribution, $f(v)$. The photon-mirror photon kinetic mixing enables a mirror nucleus (with mass and atomic numbers A', Z' and velocity v) to interact with an ordinary nucleus (presumed at rest with mass and atomic numbers A, Z) via Rutherford elastic scattering. The cross section is given by[2]:

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2} \tag{5}$$

where

$$\lambda \equiv \frac{2\pi\epsilon^2 Z^2 Z'^2 \alpha^2}{m_A} F_A^2(qr_A) F_{A'}^2(qr_{A'}) \tag{6}$$

and $F_X(qr_X)$ $(X = A, A')$ are the form factors which take into account the finite size of the nuclei and mirror nuclei. [The quantity $q = (2m_A E_R)^{1/2}$ is the momentum transfer and r_X is the effective nuclear radius]³. A simple analytic expression for the form factor, which we adopt in our numerical work, is the one given by Helm[15, 16]:

$$F_X(qr_X) = 3\frac{j_1(qr_X)}{qr_X} e^{-(qs)^2/2} \tag{7}$$

with $r_X = 1.14 X^{1/3}$ fm, $s = 0.9$ fm and j_1 is the spherical Bessel function of index 1.

The halo distribution function is given by a Maxwellian distribution,

$$
\begin{aligned}
f_i(v) &= e^{-\frac{1}{2} m_i v^2 / T} \\
&= e^{-v^2/v_0^2[i]}
\end{aligned}
\tag{8}
$$

where the index i labels the particle type $[i = e', H', He', O', Fe'...]$. The halo mirror particles form a self interacting plasma at temperature T. The dynamics of the

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³Unless otherwise specified, we use natural units, $\hbar = c = 1$ throughout.

mirror particle plasma has been investigated previously[7], where it was found that the condition of hydrostatic equilibrium implied that the temperature of the plasma satisfied:

$$T \simeq \frac{1}{2}\bar{m}v_{rot}^2 \ , \tag{9}$$

where $\bar{m} = \sum n_i m_i / \sum n_i$ $[i = e', P', He', O'....]$ is the mean mass of the particles in the plasma, and $v_{rot} \approx 254$ km/s is the local rotational velocity for our galaxy[17]. Assuming the plasma is completely ionized, a reasonable approximation since it turns out that the temperature of the plasma is $\approx \frac{1}{2}$ keV, then:

$$\frac{\bar{m}}{m_p} = \frac{1}{2 - \frac{5}{4}Y_{He'}} \tag{10}$$

where $Y_{He'}$ is the He' mass fraction. Mirror BBN studies[18] indicate $Y_{He'} \approx 0.9$, which is the value we adopt in our numerical work. Clearly, eqs.(8,9) imply that the velocity dispersion of the particles in the mirror matter halo depends on the particular particle species and satisfies:

$$
\begin{aligned}
v_0^2[i] &= \frac{2T}{m_i} \\
&= v_{rot}^2 \frac{\overline{m}}{m_i} \ . \tag{11}
\end{aligned}
$$

Note that if $m_i \gg \overline{m}$, then $v_0^2[i] \ll v_{rot}^2$. Consequently mirror nuclei have their velocities (and hence energies) relative to the earth boosted by the Earth's (mean) rotational velocity around the galactic center, $\approx v_{rot}$. This allows a mirror nuclei with mass $m_{A'} = 18 \pm 4$ GeV [consistent with a putative O' component], to provide a significant annual modulation signal in the energy region probed by dama $(2 < E_R/keV < 6)$. It turns out such a mirror dark matter component has the right properties to fully account[2] for the data presented by the DAMA collaboration[10] including the observed energy dependence of the annual modulation amplitude. Furthermore the narrow velocity distribution implied by $v_0^2 \ll v_{rot}^2$ suppresses the signal for higher threshold experiments like CDMS. The result is an explanation for the DAMA annual modulation signal completely consistent with all the other experiments.

The interaction rate for an experiment like CDMS is given by[4]:

$$
\begin{aligned}
\frac{dR}{dE_R} &= N_T n_{A'} \int \frac{d\sigma}{dE_R} \frac{f_{A'}(\mathbf{v}, \mathbf{v}_E)}{k} |\mathbf{v}| d^3v \\
&= N_T n_{A'} \frac{\lambda}{E_R^2} \int_{|\mathbf{V}|>v_{min}(E_R)}^{\infty} \frac{f_{A'}(\mathbf{v}, \mathbf{v}_E)}{k|\mathbf{v}|} d^3v \tag{12}
\end{aligned}
$$

where N_T is the number of target nuclei per kg of detector and $n_{A'} = \rho_{dm}\xi_{A'}/m_{A'}$ is the number density of halo mirror nuclei A' at the Earth's location (we take $\rho_{dm} =$

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[4]Detector resolution effects are incorporated by convolving this rate with a Gaussian distribution where $\sigma/keV = 0.2$ for CDMSII and $\sigma/keV = 0.579\sqrt{E_R/keV} + 0.021E_R/keV$ for XENON10[19]

$0.3\ GeV/cm^3$). Also, $f_{A'}(\mathbf{v}, \mathbf{v}_E)/k = exp[-(\mathbf{v} + \mathbf{v}_E)^2/v_0^2]/k$ is the A' velocity distribution ($k \equiv [\pi v_0^2(A')]^{3/2}$ is the normalization factor). Here, $\mathbf{v}$ is the velocity of the halo particles relative to the Earth, and $\mathbf{v}_E$ is the Earth's velocity relative to the galactic halo. [The bold font is used to indicate that the quantities are vectors]. Note that the lower velocity limit, $v_{min}(E_R)$, is given by the kinematic relation:

$$v_{min} = \sqrt{\frac{(m_A + m_{A'})^2 E_R}{2 m_A m_{A'}^2}}\ . \tag{13}$$

The velocity integral in Eq.(12) is standard and can easily be evaluated in terms of error functions assuming a Maxwellian dark matter distribution[16],

$$\int_{|\mathbf{V}|>v_{min}(E_R)}^{\infty} \frac{f_{A'}(\mathbf{v}, \mathbf{v}_E)}{k|\mathbf{v}|} d^3 v = \frac{1}{2 v_0 y} \left[erf(x+y) - erf(x-y) \right] \tag{14}$$

where

$$x \equiv \frac{v_{min}(E_R)}{v_0}, \ y \equiv \frac{|\mathbf{v}_E|}{v_0}\ . \tag{15}$$

The Earth's velocity relative to the galactic halo, $\mathbf{v}_E$, has an estimated mean value of $\langle \mathbf{v}_E \rangle \simeq v_{rot} + 12$ km/s, where $v_{rot} \approx 254$ km/s, the local rotational velocity[17].

Let us examine interactions of $A' = O'$ and $A' = Fe'$ on a Ge target. From Eq.(13) we find:

$$\frac{v_{min}}{v_{rot}} \simeq 1.77 \sqrt{\frac{E_R}{10\ \text{keV}}},\ \text{for } A' = O',$$

$$\frac{v_{min}}{v_{rot}} \simeq 0.74 \sqrt{\frac{E_R}{10\ \text{keV}}},\ \text{for } A' = Fe'\ . \tag{16}$$

Given that the velocity dispersion $v_0(A' = O', Fe') \ll v_{rot}$, it follows that the velocities of the halo particles relative to the Earth are distributed narrowly around the mean $\approx v_{rot}$. Therefore the interactions of the O' component will be exponentially suppressed because only O' particles in the tail of the Maxwellian distribution can lead to recoils with energies greater than the 10 keV threshold. The O' interaction rate can be determined using the DAMA measurement of $\epsilon\sqrt{\xi_{O'}}$, Eq.(2), and we have checked that the event rate in CDMSII/Ge for the O' component is indeed negligible, typically $\lesssim 10^{-2}$ events for their 1009.8 kg-days of total raw exposure. [The total CDMSII exposure consists of 397.8 kg-days for their first results[20] and 612 kg-days for their final exposure[1]]. However for a heavier component, such as $A' = Fe'$, there is no exponential suppression at or near the CDMS threshold since $v_{min}/v_{rot} \lesssim 1$. Thus, the CDMSII experiment is sensitive to a heavier component, which we take as $A' = Fe'$.[5]

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[5]Demanding $v_{min}/v_{rot} \lesssim 1$ at $E_R = 10$ keV implies $m_{A'} \gtrsim 35 m_P$. That is CDMSII/Ge is primarily sensitive to mirror elements heavier than about chlorine. By far the most abundant ordinary element heavier than chlorine is iron, and this motivates our assumption that the dominant mirror element heavier than chlorine in the mirror sector is Fe'.

The most exciting possibility is that CDMSII has seen this heavy component, which has been anticipated for a while[14]. The CDMSII/Ge event rate is $R = \int \frac{dR}{dE_R} \mathcal{E}(E_R) dE_R$, where $\mathcal{E}(E_R) \simeq 0.18 + 0.007 E_R$ is the detection efficiency for the CDMSII low energy region[1]. Adjusting this rate to give around 2 events for the total raw exposure of 1009.8 kg-days, gives a determination of $\epsilon \sqrt{\xi_{Fe'}}$:

$$\epsilon \sqrt{\frac{\xi_{Fe'}}{10^{-3}}} \approx 10^{-9} \ . \tag{17}$$

The resulting recoil energy spectrum is given in figure 1. As the figure demonstrates, the 'signal' region is in the recoil energy range 10-20 keV, which is precisely where the two events seen by CDMS were located. Observe that for $E_R \overset{<}{\sim} 18$ keV the rate falls roughly as $1/E_R^2$, which is due to the $\frac{d\sigma}{dE_R} \propto 1/E_R^2$ of the Rutherford elastic scattering cross-section. For $E_R \overset{>}{\sim} 18$ keV, the rate begins to fall even faster as v_{min}/v_{rot} moves into the tail of the Maxwellian velocity distribution. If the CDMSII experiment has really seen Fe' interactions, then this possibility can be checked by future measurements, with the bulk of the events predicted to lie in the energy region $\overset{<}{\sim} 18$ keV.
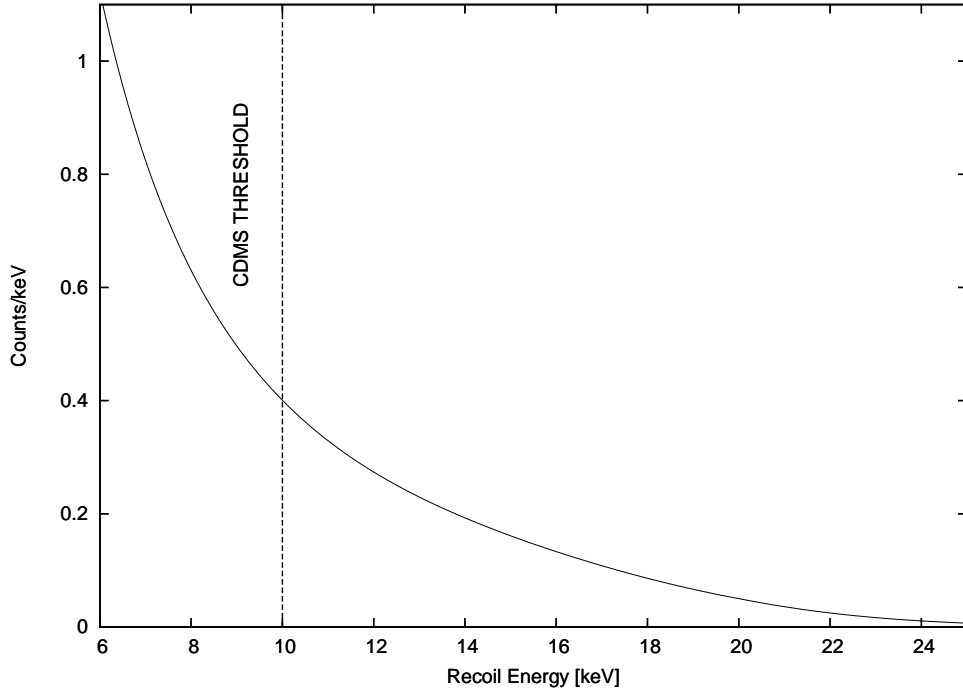

Figure 1: Recoil energy spectrum, $\frac{dR}{dE_R} \mathcal{E}(E_R) T$, predicted for the CDMSII detector for the total raw exposure of T = 1009.8 kg-days, where $\mathcal{E}(E_R)$ is the CDMS detection efficiency. We have taken parameters: $\epsilon \sqrt{\frac{\xi_{Fe'}}{1.2 \times 10^{-3}}} = 10^{-9}$, $v_{rot} = 254$ km/s which leads to around two expected events above threshold.

The XENON10 experiment[13], with their published raw exposure of 316 kg-days, has a sensitivity comparable to the CDMSII experiment. In the original XENON10 analysis[13], their threshold was assumed to be 4.5 keV, however in a subsequent study[21] a lower threshold of 2 keV was used. However, the calibration of the XENON10 detector depends on the relative scintillation efficiency $\mathcal{L}_{eff}$ which was originally taken to be constant, $\mathcal{L}_{eff} = 0.19$ in ref.[13, 21], but recent measurements[22, 23] have shown that in fact $\mathcal{L}_{eff}$ is energy dependent. The most recent measurements[23] suggest $\mathcal{L}_{eff} = 0.10 \pm 0.03$ at $E_R \simeq 8$ keV and $\mathcal{L}_{eff} = 0.07 \pm 0.03$ at $E_R \simeq 4$ keV. Given that the threshold energy is inversely proportional to $\mathcal{L}_{eff}$, it follows that the new measurments of $\mathcal{L}_{eff}$ raise the threshold from 2 keV to around 5.4 keV, with an uncertainty of roughly 30%. In figure 2 we plot the expected count rate for Fe' interactions in XENON10 for the same parameters used in figure 1: $\epsilon\sqrt{\frac{\xi_{Fe'}}{1.2\times10^{-3}}} = 10^{-9}$, $v_{rot} = 254$ km/s. As the figure suggests, for an energy threshold of 5.4 keV, we might have expected a couple of events to have been seen in XENON10, however, with such small statistics and also the significant uncertainty in the XENON10 energy calibration, there is no clear disagreement between the two experiments. Importantly XENON10 has been superseded by the XENON100 experiment with more than an order of magnitude improvement in sensitivity. XENON100 is currently in operation and should have their first results during 2010. One might reasonably expect XENON100 to see around a dozen or more events in the low energy region $E_R \overset{<}{\sim} 18$ keV if the mirror dark matter interpretation of the two CDMSII events is correct.
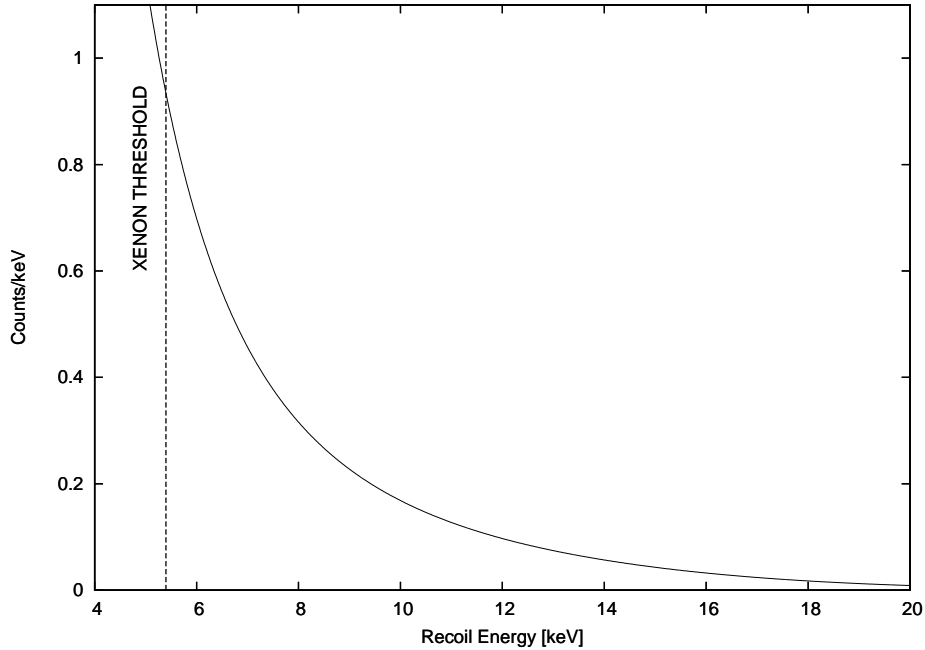

Figure 2: Recoil energy spectrum, $\frac{dR}{dE_R}\mathcal{E}(E_R)T$, predicted for the XENON10 detector with raw exposure of $T = 316$ kg-days, where $\mathcal{E}(E_R) \simeq 0.4$ is the XENON overall detection efficiency[13]. We have taken the same parameters as figure 1: $\epsilon\sqrt{\frac{\xi_{Fe'}}{1.2\times10^{-3}}} = 10^{-9}$, $v_{rot} = 254$ km/s.

We have checked that the addition of an Fe' component with $\epsilon\sqrt{\frac{\xi_{Fe'}}{10^{-3}}} \approx 10^{-9}$, does not significantly change the good fit to the DAMA/Libra annual modulation signal given by the O' component. The DAMA experiments remain the most sensitive existing experiments to the $\sim O'$ component, while the CDMSII and the other higher threshold experiments are the most sensitive probes of a heavier $\sim Fe'$ component. Thus, the CDMS and similar experiments have an important role in probing the heavy $\sim Fe'$ component which is complimentary to experiments such as DAMA/NaI and DAMA/Libra which probe the lighter O' component. Note that our estimate of $\epsilon\sqrt{\xi_{Fe'}}$ from the CDMSII events can be combined with the $\epsilon\sqrt{\xi_{O'}}$ value inferred from the DAMA/Libra experiment to yield $\xi_{Fe'}/\xi_{O'} \approx 10^{-2}$. It is interesting that this is the same order of magnitude as the corresponding quantity for ordinary matter in our galaxy and demonstrates that our combined interpretation of the DAMA/Libra experiment and the two CDMSII events is plausible.

In conclusion, we have examined the possibility that the two events seen in the CDMSII experiment are in fact mirror dark matter interactions from the anticipated[14] heavy $\sim Fe'$ component. This is actually a natural possibility given that a) mirror dark matter predicts an event rate which is sharply falling with respect to recoil energy and that b) the two observed events are in the low energy region near threshold. Importantly the mirror dark matter interpretation of the CDMSII/Ge events can be checked by on-going and future experiments, such as SuperCDMS, XENON100, and others, with the bulk of the events predicted to arise in the $E_R \overset{<}{\sim} 18$ keV region.

Acknowledgments

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